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Technical Report JSR-77-19 November 1977

ELF RADIATION FROM A NUMBER OF DISPERSED ANTENNA LOCATIONS FOR SUBMARINE COMMUNICATIONS

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NOV 29 1977

Contract No. DAHC15-73-C-0370
ARPA Order No. 2504
Program Code No. 3K10
Date of Contract: 2 April 1973
Contract Expiration Date: 30 November 1977
Amount of Contract: $3,176,255

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER JSR-77-19	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER 9
4. TITLE (and Subtitle) 6 ELF RADIATION FROM A NUMBER OF DISPERSED ANTENNA LOCATIONS FOR SUBMARINE COMMUNICATIONS,		5. TYPE OF REPORT & PERIOD COVERED Technical Report,
		6. PERFORMING ORG. REPORT NUMBER 14 SRI-JSR-77-19
7. AUTHOR(s) 10 F.W. Perkins		8. CONTRACT OR GRANT NUMBER(s) 15 DAHC15-73-C-0370, ARPA Order-2504
9. PERFORMING ORGANIZATION NAME AND ADDRESS SRI, International 1611 North Kent Street Arlington, VA 22209		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Advanced Research Projects Agency 1400 Wilson Boulevard Arlington, VA 22209		12. REPORT DATE 11 November 1977 / 13. NO. OF PAGES 13
14. MONITORING AGENCY NAME & ADDRESS (if diff. from Controlling Office) 12 15p.		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

ELF
SANGUINE
SEAFARER
SUBMARINE COMMUNICATIONS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

It is technically feasible to radiate an adequately strong ELF signal for submarine communications by utilizing a number of independent antenna sites (e.g. either 50 separate sites or 5 arrays of 10 antennas each). Each antenna must be properly phased so as to constructively add the amplitudes of the individual signals. The dispersed system makes up for the degradations caused by higher ground conductivity by use of a high power (5 megawatt) generator for each antenna. For a system composed of 50 antennas each 20 km long, the total power consumed -- 250 megawatts -- is much larger than the present Sanguine/Seafarer system but the real

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19. KEY WORDS (Continued)

20 ABSTRACT (Continued)

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ABSTRACT

It is technically feasible to radiate an adequately strong ELF signal for submarine communications by utilizing a number of independent antenna sites (e.g. either 50 separate sites or 5 arrays of 10 antennas each). Each antenna must be properly phased so as to constructively add the amplitudes of the individual signals. The dispersed system makes up for the degradations caused by higher ground conductivity by use of a high power (5 megawatt) generator for each antenna. For a system composed of 50 antennas each 20 km long, the total power consumed -- 250 megawatts -- is much larger than the present Sanguine/Seafarer system but the real estate demands are much less. The higher power per individual antenna may entail using a number of parallel cables or more deeply buring some cables to avoid environmentally unacceptable high surface magnetic fields. Lastly it is proposed that a VLF communications system link the various antenna sites.

CONTENTS

I INTRODUCTION

Because the Sanguine/Seafarer system has experienced political difficulties in deployment, the question has arisen: why not deploy a number of smaller antennas at various sites around the United States to effect the same communications mission? Answering this question raises a number of issues which include: to what accuracy must the individual antennas be phased? How many antennas must be used? Does not the higher average ground conductivity seriously degrade the antenna performance? How does one communicate with the various antenna sites?

This report will attempt to answer these questions by showing how the radiation field will depend on the parameters over which we have some control: the power into an individual antenna, its length and construction, and the ground conductivity associated with each antenna. We shall then apply these formulas to two heuristic cases: (1) 5 antenna arrays of dimensions 20 km x 20 km, an array consisting of 10 individual antennas each fed by a 5 megawatt generator and located so that the average ground conductivity is three times higher than the Michigan Seafarer site, and (2) 50 separate antennas of 20 km length, each fed by a 5 megawatt generator, and located so that the average ground conductivity is again three times higher than Michigan Seafarer site. These heuristic systems have traded off antenna length for greatly increased total power consumption. Furthermore each individual antenna will be carrying peak electric currents of roughly 3 kiloamps, so that it must, in fact, be composed of roughly 10 parallel cables to keep the surface magnetic fields below 1 gauss if this is indeed an environmental requirement.

II RADIATION FIELD OF A GROUNDED WIRE ANTENNA

The radiation magnetic field H from a single grounded loop wire antenna is well known,[1] and for our purposes can be written as

$$H = \frac{1}{4\sqrt{\pi}} \frac{I\ell\delta\omega^{3/2} e^{-\alpha r}}{c^{3/2} hr^{1/2}} \cos\phi \cos\left(\frac{\omega r}{c} - \omega t + \psi\right) (\text{amps/m}) \tag{1}$$

where

$\delta = (2/\omega\mu_o\sigma)^{1/2}$ = skin depth (meters)

I = current in wire (amps)

ℓ = antenna length (meters)

h = height of earth-ionosphere waveguide ($\approx 8 \cdot 10^4$ meters)

σ = ground conductivity - mhos/m

ϕ = azimuthal angle from antenna direction

r = range (meters)

$\omega = 2\pi \cdot (45\ \text{Hz})$

α = attenuation of earth-ionosphere waveguide (m^{-1})

c = speed of light ($3 \cdot 10^8$ m/sec)

Let us use this formula to estimate what phase variations will occur between various sites. We obtain

$$\frac{\omega\delta r}{c} \approx \pi \quad , \quad \omega^{-1} = 3 \times 10^{-3}\ \text{sec} \tag{2}$$

where $\delta r = 3 \cdot 10^6$ meters was used to estimate the difference in range between various antenna locations. Hence CONUS represents an area roughly half a wavelength in size and a collection of antennas located within CONUS can be expected to have some moderate directive properties, depending on how they are phased. To achieve phasing, absolute time must be maintained to an accuracy of 10^{-4} sec--not a difficult feat by modern time standards. Time synchronization can be updated via the VLF system proposed to communicate with the various antennas. The directivity patterns for a half-wavelength size source region are roughly 45^o in width, sufficient to subtend interesting ocean areas. Like any phased array antenna, the dispersed ELF antenna beam can be electronically steered.

Next, let us derive the formula for the total radiated field strength of an assembly of antennas. We shall assume that the antennas are all received in phase at the appropriate receiving site. The impedance of a grounded wire antenna has both resistive[1] and inductive parts.

$$R \approx \frac{\mu_o \omega \ell}{8} \tag{3}$$

$$Z \text{ inductive} \approx \frac{\mu_o \omega \ell}{2\pi} \ln\left(\frac{\delta}{\overline{S}}\right) \tag{4}$$

where $\overline{S}$ is a distance defined in Equation (12) below. We shall assume the inductance is tuned out, but note that, in any event, the resistive and inductive impedances scale the same way with length and frequency, and differ only by a modest numberical factor $\left[\ln(\delta/\overline{S}) \approx 4\right]$. Hence the power dissipated is

$$P = I^2R \tag{5}$$

and our formula for the radiated magnetic field from a single antenna becomes

$$H = \frac{1}{\sqrt{\pi\mu_o}} \left(\frac{P\ell}{\sigma}\right)^{1/2} \frac{\omega^{1/2}}{c^{3/2}\ hr^{1/2}} e^{-\alpha r} \cos\phi \cos\left(\frac{\omega r}{c} - \omega t + \psi\right) \tag{6}$$

From this formula, it is evident that the received field depends on the factor $(P\ell/\sigma)^{1/2}$ plus other factors that have little to do with antenna properties. If a system of N dispersed antennas is to be equivalent to a single large antenna, then (assuming the dispersed antennas are all in phase)

$$\left(\frac{P_i\ell_i}{\sigma_i}\right)^{1/2} N = \left(\frac{P_o\ell_o}{\sigma_o}\right)^{1/2} \tag{7}$$

where the subscripts i,o denote the small and large antennas respectively. Equation (17) can be solved directly for the required number of small antennas.

$$N = \left(\frac{P_o\ell_o\sigma_i}{P_i\ell_i\sigma_o}\right)^{1/2} \tag{8}$$

Equation (8) is our key result for comparing the effectivenss of dispersed systems versus a single large antenna. Evidently the dispersed system involves a total length $\ell = N\ell_i$ of antennas and consumes NP_i power.

III HEURISTIC DISPERSED SYSTEMS

This section starts from the ad-hoc premise that $\ell_i = 20$ km is the largest politically acceptable antenna. The present Seafarer plans, according to <u>Aviation Week and Space Technology</u>,[2] calls for $\ell_o = 4000$ km and $P_o = 16$ megawatts. If we take $\ell_i = 20$ km and power each individual antenna with $P_i = 5$ megawatts, and also assume that $\sigma_i/\sigma_o = 3$, then we find

$$N \approx 44 \quad . \tag{9}$$

It will take some 40 - 50 antennas to equal the proposed Seafarer system. The antennas can be arranged into 5 square arrays where the spacing between individual antennas within an array must be at least a skin depth ($\delta \approx 5$ km). Consequently, each 20 km x 20 km array will consist of 10 individual antennas and total power consumed by an array will be 50 megawatts. Alternatively, the 50 antennas could be located at 50 separate sites, each requiring a 20 km x 100 meter right-of-way. Evidently, a system composed partially of arrays and partially of single sites is also possible. Only 1,000 km of antenna length is involved, but the system uses 250 megawatts of power, supplied by 5 megawatt modules. From (3) we find that the impedance of a 20 km antenna is 1Ω, resulting in rms currents of 2.2 kilo amps and rms voltages of 2.2 kilovolts--both realistic values.

IV MAXIMUM CURRENTS AND SURFACE MAGNETIC FIELDS

Since both the power is higher and the individual antenna resistance is lower because of its shorter length [see (3)] in the dispersed system, the peak currents flowing in each individual antenna will be quite high:

$$I_{peak} = (2P/R)^{1/2} \simeq 3 \text{ kiloamps} \tag{10}$$

These high currents mean that the oscillating magnetic field strengths $\tilde{B}$ in the immediate vicinity of an antenna will also be quite high

$$\tilde{B} = \frac{6 \text{ gauss}}{M} \left(\frac{1 \text{ meter}}{S}\right) \left(\frac{I}{3 \text{ kiloamps}}\right) \tag{11}$$

where S is the separation between the observer and the antenna wire and M the number of cables for a single antenna. By comparison, the earth's magnetic field has a strength of 0.5 gauss.

If a 6 gauss fluctuating magnetic field is deemed an environmental hazard, then the antenna must be designed so as to reduce $\tilde{B}$. There are two approaches to this, which can be employed separately or together. The first is simply to bury the antenna cable to a depth of 10 meters so that S must always exceed 10 meters. The second is to make the antenna out of a number $M \simeq 10$ separate cables, with the separation between cables being roughly twice the buried distance. Each cable then carries a fraction

1/M of the total current, and can be correspondingly smaller and cheaper. The multicable approach also has the advantage of lowering the inductance of the antenna to the extent that the quantity $\bar{S}$ used in Equation (4) is given by

$$\bar{S} = \begin{cases} Ms & \text{multicable} \\ a_o & \text{single cable} \end{cases} \tag{12}$$

where a_o is the wire radius.

V COMMUNICATIONS TO THE DISPERSED SITES

As long as buried antennas are being put down, it seems natural to include a buried VLF receiving antenna at each site that will provide communications which are relatively secure and hard. A communications channel centered near 10 kHz will provide adequate updates of the time synchronization needed to maintain the phasing between the various ELF antennas.

VI DISCUSSION

It is clear that an effective dispersed ELF antenna system is technically possible. Roughly 50 separate antennas are required. Furthermore, it has the atractive features from a management point of view that it can be gradually built up, and will employ modules which can be produced in quantity. Political difficulties associated with a particular site will not hold up construction at other sites. Let us also note that, from Equations (3-4), the impedance which the power supply sees is not dependent on ground conductivity (which we can not precisely control) but only on antenna length (which we do control) so economies associated with serial production can be expected. We expect that 5 megawatt power sources (which are typical of submarine propulsion systems) can readily be constructed utilizing diesel engines, and that submarine batteries will provide an energy reserve in the event that the diesel fails. Lastly, we noted that if high surface magnetic fields are environmentally unacceptable, they can be reduced by constructing an individual antenna with roughly 10 parallel smaller (and hopefully cheaper) cables.

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2. <u>Aviation Week</u> and <u>Space Technology</u>, p 51 (April 4, 1977).

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